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Research Article

Modeling the Impact of Microcrack Healing on the Compressive Strain of Asphalt Concrete Under Dynamic Compression

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Keywords

Microcrack healing, Asphalt concrete, Compressive stress, Dynamic, Cmpressive microstrain, Modeling.

Abstract

The utilization of the self-healing behavior of cracked asphalt concrete pavement is a sustainable approach for extending the fatigue life and reserving its mechanical properties. In the present investigation, cylindrical specimens of asphalt concrete mixture were prepared with the optimum binder requirement. The specimens were subjected to dynamic compressive stresses at a constant stress level of 138 kPa. The dynamic testing was conducted using 0.1 seconds of loading and 0.9 seconds of rest period at 20°C environment with the aid of pneumatic repeated load system PRLS. The load application was terminated after 900 load repetitions. The specimens were stored in an oven for 60 minutes at 120°C to allow the generated microcracks in the mixture to heal, then the specimens were subjected to another round of dynamic stresses. The compressive strain in terms of (total, permanent, and resilient) were monitored by LVDT which was positioned on the specimens. The influence of the healing process on the deformation was modelled. It was concluded that the microcracks healing process exhibits significant influence on the compressive strain of asphalt concrete under the applied dynamic compressive stresses. After 900 load repetitions, the compressive strain declined by (30, 28.5 and 66.7) % for (total, permanent, and resilient) compressive strain respectively after practicing microcrack healing process. Mathematical models of the compressive strain parameters before and after the healing process exhibited high coefficients of determination and may be adopted in the design of sustainable asphalt concrete mixture.

1. Introduction

The self-healing concept of asphalt concrete exhibits an excellent potential for extending its fatigue life. Ghazali et al., 2021 [1] revealed that self-healing can be considered as a sustainable issue since it can reduce the need for more production of asphalt mixture by utilization of the existing asphalt mixture. Promotion of crack closer by the capability of asphalt as a self-healing material has been proven and its ability to heal was investigated by Abejon, 2021, [2]. Asphalt concrete is a self-healing material which exhibits the capability of restoring part of its functionality as reported by Garcia et al., 2013, [3]. Such behavior usually exists due to the potential of asphalt cement binder to behave like a Newtonian fluid at temperatures ranging from (70 to 30) °C, depending on the type of asphalt. Xu et al., 2024, [4] investigated the healing characteristics of asphalt cement through the assessment of fatigue-healing performance of its fractions and its characterization at the molecular level. The test results indicated that aromatics exhibit the closest similarity to original asphalt cement in flowing behavior, which is also reflected in the healing performance. The healing performance of asphaltenes and resins are extremely limited while that of saturates was comparable to fluid. Wan et al., 2024. [5] introduced a novel combined healing system for sustainable asphalt concrete. The mechanical performance, morphological structure, and thermal resistance were characterized respectively. The healing levels of asphalt concrete were evaluated after cyclic loading and microwave irradiation. It was concluded that the novel combined healing system provides a new way of pavement maintenance strategy under the background of low carbon maintenance. Sarsam and Al Tuwayyij, 2020, [6] investigated the healing performance of asphalt concrete by observing the recovery of the resilient modulus after healing. It was concluded that implementation of induction heating and iron filling had exhibited a great influence on stiffening of asphalt concrete as compared with external heating technique. Vo et al., 2020, [7] stated that the micro crack healing level declined as the healing cycles proceed and declined with the increment in the maximum temperature of operation for the specific grade of asphalt cement binder. Mahdi and Sarsam, 2020, [8] investigated the microcrack healing process of recycled asphalt concrete when SBR and carbon black are implemented as additives. The variation in the resilient modulus and permanent deformation under dynamic indirect tensile load cycles with different applied loads before and after healing were identified. Ajam et al., 2016, [9] stated that healing of microcracks in asphalt concrete mixture can occur due to temperature increases within or surrounding the pavement layer. However, in the microcracking range, this may increase the useful fatigue life of the pavement. Sarsam, 2019, [10] reported that cracks may develop in flexible pavement because of repeated traffic loads or environmental impact. However, if enough energy is given to the system, it will start the healing process, and if enough time is given to the process, it may even close completely. Grossegger, 2019, [11] revealed that the self-healing of microcracks alone is not the perfect solution to an infinite damage-recovery cycle since there are huge uncertainties during the healing process. Such uncertainties which influence the self-healing of asphalt concrete include the level of damage and the time spot when self-healing occurs, type of crack (cohesive or adhesive), ageing stage, the contribution of self-healing during the damage periods, and the environmental conditions, such as temperature and humidity, and type and degree of foreign substances that was filling the crack. According to Tabakovic and Schlangen, 2015, [12] the self-repairing or self-healing property of asphalt concrete material can be referred to as its ability to substantially return to its original condition, proper operating state before exposure to susceptible environment or a dynamic loading and can make the necessary adjustments to restore its behavior to normality and exhibit ability to resist the formation of defects and irregularities. Sarsam, 2021, [13] assessed the micro crack

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healing process of asphalt concrete specimens and its influence on the deformation parameters under the action of repeated flexural and compressive stresses. Significant variation in the deformation parameters under repeated flexure and compressive stresses due to healing had been detected. Dai et al. 2013, [14] revealed that the healing behavior of asphalt mixture is a form of self-recovery capability of asphalt materials under environmental conditions, and specific loading especially during rest time. Sun et al. 2018, [15] observed an ongoing event between the fatigue process and healing in asphalt pavement during its service life. It was revealed that such process was noticed to be significantly dependent upon the variations in the asphalt pavement temperature. Ruiz-riancho et al., 2021, [16] stated that the self-healing of asphalt concrete is a process which occurs mainly due to the viscosity of the binder and the gravitational forces acting on the asphalt cement. Roque et al., 2013, [17] presented a test suitable for evaluating the healing behavior in asphalt concrete mixtures. The test consists of practicing damage tests by dynamic loading followed by a healing phase. The resilient modulus evaluation is performed during the healing phase to measure the healing in terms of recovery of the modulus. It was revealed that the decline in the resilient modulus of asphalt concrete mixture while practicing the dynamic load cycles is a significant indication of accumulation of microdamage during the damage phase. However, the recovery of resilient modulus during the healing phase is an indication of healing process or damage recovery. Xu et al. 2021, [18] stated that the fundamental of self-healing process in asphalt concrete mixture depends on the initiation of a mobile phase during the rest period which gradually results in crack closure. The self-healing material will regain a certain rate of its functionality where the asphalt binder can diffuse and flow to close its microcracks when it is not exposed to loads. Sarsam and Husain, 2016, [19] reported that Crack healing cycles exhibit positive influence on the resilient modulus of asphalt concrete. One healing cycle had increased the resilient modulus by 100% as compared with reference mix under indirect tensile stresses. Liu et al., 2017, [20] stated that the healing of asphalt concrete mixtures is influenced by external conditions, propagation of micro crack and its change to macrocracks results from loading level, consistent loading, ageing, number of load repetitions, and moisture conditions. The self-healing of asphalt concrete is influenced by the van Waals forces between molecules and the hydrogen bond. Sarsam, 2021, [21] reviewed the potential of crack healing, it was revealed that the sustainability of flexible pavement could be achieved by considering the micro crack healing concept to preserve and enhance the durability of asphalt concrete pavement in terms of fulfilling's the structural and functional performance. It was concluded that the process of healing can be used to balance the damage process and can be optimized by considering the sensitivity of asphalt concrete to environmental conditions such as temperature, material properties, and confining compressive and tensile stresses applied.

The aim of the present work is to investigate and model the influence of microcrack healing process on the flexural strain parameters of asphalt concrete. Such models may simulate the actual field conditions of environment variations between day and night in summer, and or seasonal variation. Asphalt concrete beam specimens will be prepared and subjected to dynamic compressive stresses under controlled stress conditions. After 50 % of the expected fatigue life of the mixture, the test will be terminated, and the specimens will practice microcrack healing. Specimens will be subjected to another round of dynamic compressive stresses and the variation in the compressive strain parameters (total, permanent, and resilient) will be monitored and modelled.

2. Materials and Methods

2.1. Asphalt Cement

The asphalt cement of 42 penetration grade, 48.9 °C softening point, and a specific gravity of 1.04 was implemented; it was obtained from Daura Refinery. The physical properties of the asphalt cement after practicing the thin film oven test are a retained penetration of 60 %, and loss in weight of 0.34 %. The testing was conducted as per the ASTM, 2015, [22] testing procedures.

2.2. Coarse Aggregate

Crushed coarse aggregate was brought from Al-Nibaee quarry and implemented in this work. Its bulk specific gravity is 2.680, the water absorption is 0.42 % and the percentage wear was 21.7 %.

2.3. Fine Aggregate

Fine aggregate was brought from Al-Nibaee quarry. The bulk specific gravity is 2.630, while the water absorption is 0.54 %.

2.4. Mineral Filler

Ordinary Portland cement was implemented. Its apparent specific gravity is 3.1 and the specific surface area is 315 (m^2/kg). 98 % of the cement is finer than 75 microns.

2.5. Selection of overall Aggregate Gradation

The overall gradation that was selected in this study follows SCRB R/9, 2003, [23] specification for Hot-mix asphalt paving mixtures usually used for wearing course with aggregate nominal maximum size of (12.5 mm). Figure 1 exhibits the gradation for wearing layer.

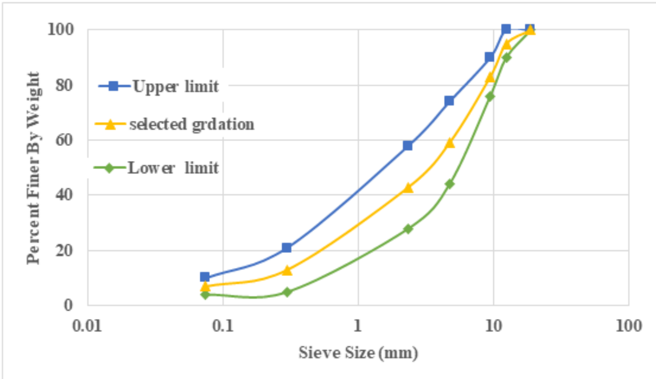

Figure 1. Gradation of Aggregate for Wearing Course as per SCRB, 2003, [23]

2.6. Preparation of Asphalt Concrete Mixture, slab samples and beam specimens

The combined aggregate mix was heated to 160°C, while the asphalt cement was heated to 150°C, then added to the aggregates and mixed thoroughly for three minutes using mechanical mixer until a homogeneous mixture is achieved. The optimum percentage of asphalt cement was obtained from previous work by Sarsam and Jasim, 2017, [24] and implemented. The compaction cylindrical mold (10.2 Cm in diameter and 20.3 Cm in height) used in this work was capable of production of specimen of 10.16 Cm in diameter and 12.7 Cm in height. The mold was heated to 150 °C, then the asphalt concrete mixture was transferred to heated mold, laid and spread uniformly with a heated spatula, then subjected to static compaction of 30 kN load applied through steel cylinder. The applied pressure was maintained for three minutes at 150°C to achieve the target density and thickness. The mold was left for 24 hours and then the specimen was extruded from the mold.

2.7. Testing for Fatigue by Implementing the Dynamic Compression Test

The specimens were subjected to dynamic axial compressive loading using the pneumatic repeated load system (PRLS). The test was performed on cylindrical specimens, 10.16 Cm in diameter and 12.7 Cm in height. In this test, dynamic compressive loading was applied to the specimen and the axial compressive strain was measured under the different loading repetitions. Compressive loading was applied in the form of rectangular wave with a constant loading frequency of 60 cycles per minute and includes 0.1 second load duration and 0.9 second rest period. The stress level of 138 kPa and an environment of 25°C were used during the tests. The specimen was left in the conditioned chamber for one hour at the testing temperature of 25°C to allow for uniform distribution of temperature within the specimen. LVDT (Linearly Variable Differential Transformer) was implemented to monitor the compressive strain parameters of the specimen under each load cycle. Then, the recorded data was analyzed for finding strain at any number of load cycles desired for every test as recommended by Sarsam and Husain, 2016, [25]. The test allows for the initiation of micro cracks, and was stopped after 900 repetitions, then specimens were withdrawn from the testing chamber, and the specimens were stored in an oven for 60 minutes at 120°C to allow the generated microcracks in the mixture to heal, then the specimens were subjected to another round of dynamic stresses. Specimens were subjected to another round of dynamic compressive stresses and the variation in the compressive strain parameters (total, permanent, and resilient) were monitored and modelled. Figure 2 demonstrates the PRLS test chamber while Figure 3 exhibits the close view of test setup.it was felt that such testing methodology may represent the actual field conditions where the asphalt concrete pavement practices the daily and seasonal variations in the environment especially during summer season.

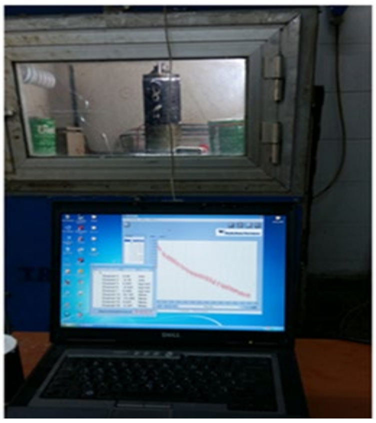

Figure 2. The PRLS test chamber

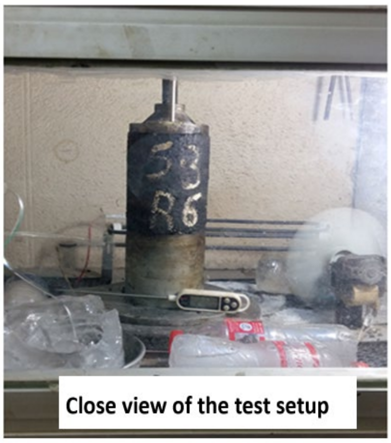

Figure 3. close view of test setup

3. Test Results and Discussions

Figure 4 demonstrates the compressive strain parameters of control asphalt concrete mixture. It can be noticed that there are two stages in the deterioration of asphalt concrete when practicing the dynamic loading before failure. During the first (primary) stage, the rate of strain is high at initial loading repetitions (up to 100 repetitions).

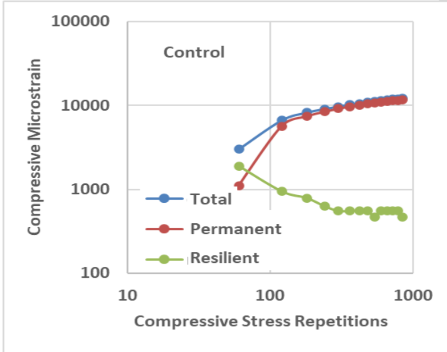

Figure 4. Compressive microstrain parameters of control mixture

As compressive stress repetitions increase, such high strain trend gently decreases in the second (secondary) stage, the strain rate is regarded as being constant and gentle, while strain increases steadily. The total and the permanent compressive strain increase while the resilient strain decline with further increment in loading. Similar behavior was reported by Ziari et al., 2007, [26]. This may be attributed to the initiation of microcracks into the structure of asphalt concrete mixture. At 900 load repetitions, the total and the permanent strain rises sharply by (3.0 and 9.5) folds respectively, while the resilient strain declines by 60.7 % as compared with the case of primary stage of loading. Such behavior may be attributed to the flexibility of the (control) asphalt concrete mixture.

Figure 5 exhibits the influence of microcrack healing on the compressive strain parameters of asphalt concrete mixture. it can be revealed that After practicing the microcrack healing process, distinguishing the failure stages is not significant in general for total and permanent strain. The trend of failure exhibits an increment in smooth and gentle mode as the dynamic loading proceeds for the total and permanent strain. However, the resilient strain showed sharp decline at the third stage of failure.

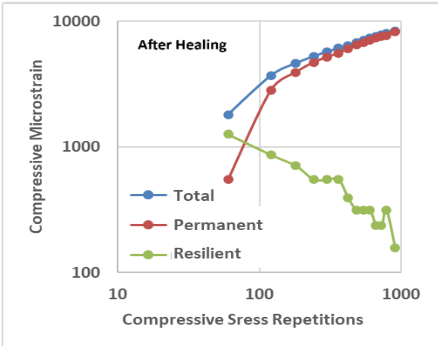

Figure 5. Compressive microstrain parameters of mixture after healing

At 900 load repetitions, the total and the permanent strain rises gently by (3.6 and 14) folds respectively, while the resilient strain declines by 87.5 % as compared with the primary stage of loading. It can be detected that after practicing the microcrack healing, the initial compressive strain declined by (39.4, 50, and 33.3) % for (total, permanent, and resilient) compressive strain respectively as compared with that of the control asphalt concrete mixture. On the other hand, the compressive strain at failure declined by (30, 28.5, and 66.7) % after practicing the microcrack healing process for (total, permanent, and resilient) compressive strain respectively as compared with that of the control asphalt concrete mixture. Such significant variations in the compressive strain parameters before and after the healing process could be related to the stiffening of the asphalt binder during the healing process as well as to the microcrack healing process which fills the voids, stiffen the binder, and increase the cohesion between the binder particles and adhesion between the aggregates and binder. Bochove, 2016, [27] and Tang et al., 2016, [28] reported similar behavior.

Table 1 demonstrates the mathematical models of the compressive strain parameters of the control asphalt concrete specimens. The polynomial models in general exhibits high coefficients of determination. It can be noticed that resilient strain decline from the early stages of loading with further increment in loading cycles. This may be attributed to the higher total and permanent strain occurred throughout the loading period.

Table 2 demonstrates the mathematical models of the compressive strain parameters of the asphalt concrete specimens. After practicing the microcrack healing process. The polynomial models in general exhibits high coefficients of determination. It can be noticed that resilient strain declines since the early stages of loading, then continues with further increment in loading cycles. This may be attributed to the stiffer mixture obtained after microcrack healing process. However, higher total and permanent strain are shown throughout the loading period.

Table 1. Mathematical Models of the compressive strain parameters before healing

Type of deformation	Mathematical model	R^2
Total	Y= - 0.0198 x^2 + 26.575 x + 3088.5	93
Permanent	Y= - 0.0236 x^2 + 30.946 x + 1430.8	91
Resilient	Y= + 0.0038 x^2 – 4.3714 x + 1657.7	72
Y= Compressive strain (microstrain		
x= Compressive stress repetitions		

Table 2. Mathematical Models of the compressive strain parameters after healing

Type of deformation	Mathematical model	R^2
Total	Y= - 0.009 x^2 + 15.068 x + 1770.2	96
Permanent	Y= - 0.0108 x^2 + 17.829 x + 534.82	96
Resilient	Y= + 0.0019 x^2 – 2.7612 x + 1235.4	91
Y= Compressive strain (microstrain		
x= Compressive stress repetitions		

4. Conclusions

Based on the testing and limitations of materials, the following conclusions can be addressed.

- At 900 load repetitions, the total and the permanent strain for control mixture rises sharply by (3.0 and 9.5) folds respectively, while the resilient strain declines by 60.7 %.
- At 900 load repetitions, the total and the permanent strain rises gently by (3.6 and 14) folds respectively, while the resilient strain declines by 87.5 % as compared with the primary stage od loading.
- After practicing the microcrack healing, the initial compressive strain declined by (39.4, 50, and 33.3) % for (total, permanent, and resilient) compressive strain respectively as compared with that of the control asphalt concrete mixture.
- The compressive strain at failure declined by (30, 28.5, and 66.7) % after practicing the microcrack healing process for (total, permanent, and resilient) compressive strain respectively as compared with that of the control asphalt concrete mixture.
- Mathematical models of the compressive strain parameters before and after the healing process exhibited high coefficients of determination and may be adopted in the design of sustainable asphalt concrete mixture.

Declaration of Conflict of Interests

The author declares that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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